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Multi-year carbon budget of a mature commercial short rotation coppice (SRC) willow plantation

Carbon balance of willow coppice

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Abstract

Energy derived from second generation perennial energy crops is projected to play an increasingly important role in the decarbonisation of the energy sector. Such energy crops are expected to deliver net greenhouse gas emissions reductions through fossil fuel displacement and have potential for increasing soil carbon (C) storage. Despite this, few empirical studies have quantified the ecosystem-level C balance of energy crops and the evidence base to inform energy policy remains limited. Here, the temporal dynamics and magnitude of net ecosystem carbon dioxide (CO₂) exchange (NEE) were quantified at a mature short rotation coppice (SRC) willow plantation in Lincolnshire, United Kingdom, under commercial growing conditions. Eddy covariance flux observations of NEE were performed over a four year production cycle and combined with biomass yield data to estimate the net ecosystem carbon balance (NECB) of the SRC. The magnitude of annual NEE ranged from -147 ± 70 to -502 ± 84 g CO₂-C m⁻² year⁻¹ with the magnitude of annual CO₂ capture increasing over the production cycle. Defoliation during an unexpected outbreak of willow leaf beetle impacted gross ecosystem production, ecosystem respiration and net ecosystem exchange during the second growth season. The NECB was -87 ± 303 g CO₂-C m⁻² for the complete production cycle after accounting for C export at harvest (1183 g C m⁻²), and was approximately CO₂-C neutral (-21 g CO₂-C m⁻² year⁻¹) when annualised. The results of this study are consistent with studies of soil organic C which have shown limited changes following conversion to SRC willow. In the context of global decarbonisation, the study indicates that the primary benefit of SRC willow production at the site is through displacement of fossil fuel emissions.

Introduction

Meeting global and national energy security whilst avoiding dangerous climate change represents a major scientific and political challenge (IPCC, 2014; Smith et al., 2013).

Addressing this challenge requires decarbonisation efforts across all sectors and biomass from perennial energy crops can contribute by delivering renewable energy with a lower greenhouse gas (GHG) intensity relative to fossil fuels (Creutzig et al., 2015). In the future, energy crops with C capture and storage (BECCS) might also prove viable for delivering negative carbon dioxide (CO₂) emissions required to meet national and international GHG emissions reductions targets (Energy Technologies Institute, 2015; Rosen, 2018). Whilst delivering genuine net GHG emissions reductions requires a full assessment of all biogenic GHG emissions from cultivation to energy production (Thornley, Gilbert, Shackley, & Hammond, 2015), for low input perennial (second generation) bioenergy crops, it is generally accepted that the major determinant of the site-level GHG balance relates to changes in soil organic carbon (SOC) following land use change to bioenergy (Richards et al., 2017), which in turn is modified by site-specific management practices (Qin et al., 2018).

Short rotation coppice (SRC) willow (*Salix* spp.) is a second generation (e.g. non-food) energy crop that has been planted over a wide geographical range in the UK and northern areas of continental Europe (Don et al., 2012; Karp and Shield, 2008; Rowe et al., 2016).

SRC exploits fast growing woody perennial species that regrow rapidly after harvesting at short (e.g. 2 to 4 year) intervals (Dimitriou, Mola-Yudego, Aronsson, & Eriksson, 2012).

Managing willow as SRC aims to maximise biomass yields with limited input requirements, resulting in high energetic returns (Rowe et al., 2011). Compared to annual crops, there is potential to enhance soil C storage under perennial SRC as a function of high productivity,

regular C inputs from litter and fine root turnover, and minimal tillage requirements (Karp & Shield, 2008). However, it remains uncertain whether perennial cropping systems capture enough atmospheric CO₂ to totally offset GHG emissions produced over the complete bioenergy life cycle (Robertson et al., 2017; Rowe et al., 2016).

Detecting changes in SOC under SRC is challenging. The rate of change in SOC is slow and many decades may be required to reach a new equilibrium following land use change (Nemo et al., 2017; Smith, 2004). In contrast to methods employing direct measurements of changes in soil C (Rowe et al., 2016), tracking year on year C fluxes from photosynthetic uptake versus plant and soil respiration can provide a means of understanding the overall trajectory of a system before changes in SOC become detectable. This requires multiple years of data to derive consensus, as the net ecosystem exchange (NEE) of CO₂ is highly dynamic across multiple timescales (e.g. Stoy et al., 2005), responding to time since establishment and harvest, management interventions and climatic forcing. The latter drives plant and phenology and productivity, influences site-level management decisions (Caslin, Finnan, Johnston, McCracken, & Walsh, 2015) and controls decomposition processes in litter and soils (Davidson & Janssens, 2006).

The most effective way of measuring the short term dynamics in net ecosystem CO₂ exchange is the eddy covariance (EC) technique which quantifies turbulent surface-atmosphere exchanges of energy and mass (Baldocchi, 2003; Baldocchi, 2014) at ecosystem scale. In contrast to longer-term perspectives provided by stock-based C accounting (Agostini, Gregory, & Richter, 2015; Dimitriou et al., 2012; Berhongaray, Verlinden, Broeckx, Janssens, & Ceulemans, 2017; Rowe et al., 2016), EC provides direct, high

frequency and quasi-continuous observations of NEE from a flux footprint representative of tens to hundreds of meters (Arriga et al., 2017; Baldocchi, 2003). To date, a limited number of EC studies have focused on the early stages of land use change to SRC willow (Grelle, Aronsson, Weslien, Klemedtsson, & Lindroth, 2007; Harris, Spake, & Taylor, 2015; Harris et al., 2017); however, commercial SRC plantations have suggested economic life spans of twenty to thirty years (Don et al., 2012) and empirical data obtained at young SRC sites may not reflect the dynamics of mature plantations (Walter, Don, & Flessa, 2015). In order to inform bioenergy policy, observational data from across a wider range of SRC willow production systems are required for model development and testing (e.g. Dondini et al., 2016), and as inputs to bioenergy life cycle analyses (e.g. Agostini et al., 2015) and geographical assessments (e.g. Hammar et al., 2014; Pogson et al., 2016).

This study reports multi-year flux observations (January 2014 to November 2017) of NEE obtained at a mature commercial SRC willow plantation in Lincolnshire, UK. The SRC is representative of an age class of SRC willow plantations established during the early 2000s. Flux measurements are reported for a near-complete, four-year production cycle. An unexpected outbreak of willow beetle (*Phratora vulgatissima*) and leaf defoliation during the second and to a lesser degree the third year of the observation period provided an opportunity to follow the effects of insect defoliation on ecosystem CO₂ fluxes. Outbreaks of willow leaf beetle and associated reductions in biomass yield are widely recognised as a major economic pest for commercial SRC production (Bjorkman & Eklund, 2006; Bjorkman, Hoglund, Eklund, & Larsson, 2000). Despite such recognition, it is unclear how frequently such outbreaks occur in commercial SRC production systems, or how such events might impact the sustainability and profitability of bioenergy production if large scale plantings required to meet bioenergy targets are realised.

The overall aim of the study was to characterise the magnitude and dynamics of CO₂ exchange at the mature SRC willow plantation. The specific objectives of the current study were to: (i) to characterise seasonal and inter-annual variability in net ecosystem CO₂ exchange (NEE) and its component fluxes; and (ii) to quantify the net ecosystem CO₂-C budget (NECB) of the mature SRC plantation.

Materials & methods

Site description

The flux measurement site is a 9.4 ha commercial SRC willow plantation located approximately 10 km north of Lincoln, England, United Kingdom. The climate is temperate maritime (Cfb, Köppen, Volken, & Brönnimann, 2011), characterised by cool summers, mild winters and a thermal growing season from April to October. The closest UK Met Office station with complete long-term records (RAF Waddington, 53° 10' 30"; N; 0° 31' 15.6" W 68 m absl) is located approximately 15 km south of the observation site. Mean (\pm standard deviation, SD) annual air temperature was $9.8 \pm 0.7 \text{ }^\circ\text{C}$ for the 1981 to 2010 period. July ($16.9 \pm 1.2 \text{ }^\circ\text{C}$) is the warmest month and January ($4.0 \pm 1.6 \text{ }^\circ\text{C}$) is the coldest. The mean annual (1981 to 2010) precipitation was $614 \pm 93.5 \text{ mm year}^{-1}$. Precipitation is distributed approximately evenly over the annual cycle. South westerly winds predominate at this location.

Soils (Beccles 1 association) at the site are seasonally waterlogged fine loams and clays overlying Charnmouth mudstone (Drewer, Finch, Lloyd, Baggs, & Skiba, 2012). This soil association has a spatial distribution of approximately 1745 km² across England and Wales (Cranfield University, 2018). Sand, silt and clay fractions (%) in the upper 0.3 m of the soil

profile were previously reported at 49%, 36% and 15%, correspondingly (Robertson et al., 2017). Total organic C and nitrogen (N) content in this soil layer were 68.3 and 11.0 t ha⁻¹, respectively (Rowe et al., 2016). Soil bulk density and pH were previously reported at 1.4 ± 0.2 g cm⁻³ and 5.8 ± 0.3 (Drewer et al., 2012), correspondingly.

Land management

The SRC willow plantation was established on former arable land in 2000. The regional crop rotation prior to conversion was winter wheat (*Triticum aestivum*) with oilseed rape (*Brassica napus*) and spring barley (*Hordeum vulgare L.*) as break crops. During conversion, the field was cultivated (plough, power harrow and flexi-tyne) and sprayed with non-selective weedkiller (Glyphosate). A mixture of five commercial varieties of *Salix viminalis* were randomly planted as an integrated mix (block planted) across the field with the aim of minimising the impacts of pests and diseases. Approximately 15000 willows ha⁻¹ were planted in double rows with within and between row spacing of 0.75 m and 1.5 m, correspondingly. The plantation was cut back (coppiced) in 2001 to encourage branching and is typically managed using three year rotation cycles. Stool survival in 2018 based on counts from twenty random 4 by 5 m plots was 80%. During this study, an outbreak of willow leaf beetle (*Phratora vulgatissima*) resulted in severe defoliation and subsequently low biomass accrual during the second year of the rotation cycle (see below). In response to this, the land manager delayed the harvest by one year in order to maximise biomass yield and economic return. Biomass was harvested on 2017-09-27 using specialized equipment cutting the willow directly to chip. Other than harvesting, the plantation has been minimally managed with the most recent input in 2011, when micronutrients (Fibrophos 0.5 Mg ha⁻¹ and lime) and

compost wood waste (15 Mg ha^{-1}) where applied following harvest. The site is rain fed with no requirement for irrigation.

Crop development

The SRC plantation crop was characterised by changes in aboveground biomass over the production cycle. At the start of the observation period in January 2014, willow stools were dormant and areas of bare soil and litter remaining from the previous harvest were present across the site. In the first year of the rotation (2014), bud burst occurred during April with notable new shoot extension and leaf area by May. Full canopy closure was observed by July 2014. The SRC stand attained a mean height of $2.0 \pm 0.02 \text{ m}$ by autumn 2014. In subsequent years, new shoots developed at the apex of the preceding season's woody growth resulting in earlier leaf displays compared to 2014. Mean stand height had increased to $2.9 \text{ m} \pm 0.2 \text{ m}$ by June 2015 and was $3.5 \pm 1.2 \text{ m}$ at the time of harvest in 2017. The active growth phase lasted from April to October in all years, but bud burst and leaf out occurred notably earlier during warmer than average conditions in spring 2017 compared to other years of the rotation.

Higher than average air temperatures during autumn 2016 also resulted in a later onset of leaf senescence and fall relative to other years.

Willow leaf beetle

A *P. vulgatissima* population was observed in the plantation during all years of the observation period. Leaf damage caused by *P. vulgatissima* herbivory was most severe during the second year (2015) of the rotation cycle. As damage from a severe pest outbreak was not expected no quantitative measures of beetle density were made, however, in 2015 the population of *P. vulgatissima* reached a density at which progressive, widespread and severe

leaf damage was observed on all willow trees between July and September (Fig 1). The majority of willow leaves were brown and skeletonised by July (Fig. 1b) and did not recover before the end of the growing season (Fig. 1c). In 2014, 2016 and 2017, herbivory by *P. vulgatissima* was more selective and localised. Herbivory in 2016 and 2017 mainly affected young leaves (between July-August) on certain individual willow stools, possibly caused by preferential feeding on certain willow varieties. Observed leaf damage in 2016 and 2017 was mostly replaced by compensatory growth by September.

Flux instrumentation

Sensible and latent heat fluxes (LE and H, respectively) and NEE were monitored using an open-path eddy covariance (EC) system. Flux observations commenced on 2014-01-09 during the winter dormant period following the previous harvest (on 2013-10-31) and ended on 2017-11-26. A Solent R3-50 sonic anemometer (Gill Instruments Ltd., Lymington, UK) was used to measure the three components of atmospheric turbulence (u , v , w ; m s^{-1}) and sonic temperature (T_{sonic} ; $^{\circ}\text{C}$). An LI7500 infrared $\text{H}_2\text{O}/\text{CO}_2$ gas analyser (IRGA; LI-COR Biosciences, Lincoln, Nebraska, USA) was used to measure the atmospheric mass density of vapour ($\text{g H}_2\text{O m}^{-3}$) and CO_2 ($\text{mg CO}_2 \text{m}^{-3}$) and barometric pressure (P_{air} ; kPa). Air temperature (T_{a} ; $^{\circ}\text{C}$) and relative humidity (RH; %) were measured at a height of 2 m using a HC2A-S probe (Rotronic, Bassersdorf, Switzerland). EC sensors were sampled and logged at 20 Hz using a CR3000 Micrologger (Campbell Scientific Inc., Logan Utah, USA). The EC system was installed at the centre of the plantation to maximise the available fetch under prevailing wind conditions. The available fetch was limited to 110 m to the north of the EC tower, extending to 210 m to the southwest. EC sensors were mounted on an extendible pneumatic mast (Clarke Masts Ltd., Binstead, UK), the height of which was increased several

times per growing season, to maintain the EC measurement height at a minimum of 2 m above the willow canopy.

Ancillary measurements

A range of micrometeorological measurements were made from a separate scaffold tower located at the northern end of the plantation approximately 110 m from the EC mast. The net radiation (R_{net} ; W m^{-2}) and its incoming and outgoing short- and long-wave components (SW_{in} , SW_{out} , LW_{in} and LW_{out} , respectively; W m^{-2}) were measured above the canopy using a CNR1 net radiometer (Kipp & Zonen BV, Delft, The Netherlands). Secondary measurements of air temperature (T_{air} , °C) and relative humidity (RH, %) were made at 7 m above the soil surface using a HC2A-S probe (Rotronic, Bassersdorf, Switzerland).

Soil physics were measured close to the scaffold tower. Soil heat fluxes (G ; W m^{-2}) were monitored using two HFP01 soil heat flux (Hukseflux BV, BV, Delft, The Netherlands) plates installed 0.03 m below the soil surface. Soil temperature (T_{soil} ; °C) was measured at a depth of 0.05 m using two PT107 soil thermocouples (Campbell Scientific Inc.). Soil volumetric water content (VWC; $\text{m}^3 \text{m}^{-3}$) was measured using two CS616 time domain reflectometers installed vertically to measure the VWC of the top 0.3 m of the soil profile (Campbell Scientific Inc.). Precipitation was measured using a tipping bucket rain gauge (P; 0.5 mm sensitivity; Observator Instruments BV, The Netherlands) installed in an open area of low grass approximately 10 m north of the plantation. These sensors were scanned at 0.1 Hz and logged as thirty minute means (sums for precipitation) using a CR1000 Datalogger (Campbell Scientific Inc.).

Flux data handling

Thirty minute flux densities (hereafter fluxes) of sensible and latent heat (LE and H) and net ecosystem CO₂ exchange (NEE) were computed from the raw EC data using EddyPRO® Flux Calculation Software (LI-COR Biosciences, Lincoln, Nebraska, USA; Fratini and Mauder, 2014). Raw EC data were screened for statistical outliers (Mauder et al., 2013) and other physically implausible values (Vickers & Mahrt, 1997). Sonic anemometer data were rotated using a two-dimensional coordinate rotation procedure (Wilczak, Oncley, & Stage, 2001) and corrected for imperfect cosine response (Nakai, Van Der Molen, Gash, & Kodama, 2006). Time lags between the vertical wind speed and concentration measurements were removed using a cross-correlation procedure. Uncorrected fluxes were calculated as the mean covariance between the vertical wind speed (w) and the respective atmospheric scalar using thirty minute block averages (Baldocchi, 2003). Fluxes were corrected for high (Moncrieff et al., 1997) and low frequency cospectral attenuation (Moncrieff, Clement, Finnigan, & Meyers, 2004). H fluxes were corrected for the influence of atmospheric humidity (Schotanus, Nieuwstadt, & Bruin, 1983). LE then CO₂ fluxes were adjusted for fluctuations in atmospheric density (Webb, Pearman, & Leuning, 1980). Random uncertainties for thirty minute flux observations related to sampling error were estimated as standard deviations derived from a variance of covariance approach (Finkelstein and Sims, 2001). No CO₂ profile measurements were available to estimate the CO₂ storage term. CO₂ storage was assumed negligible at the low observation height and NEE was assumed equal to the turbulent CO₂ flux. The micrometeorological sign convention is adopted where positive values represent fluxes from ecosystem to atmosphere and negatives describe the reverse.

Quality control

Quality control (QC) procedures were applied to ensure only high quality turbulent flux data were retained for analysis. Thirty minute flux data were screened for statistical outliers using the median absolute deviation approach (Sachs, 2013) following recommendations in Papale et al. (2006). Fluxes were also excluded when: the results of the stationarity (steady-state) test result deviated by more than 100 % (Foken et al., 2004); when the automatic gain control (AGC) of the LI7500 was >10 % above its baseline (Ruppert, Mauder, Thomas, & Lüers, 2006); and when fluxes were outside the range $-200 < H > 500 \text{ W m}^{-2}$, $-100 < LE > 600 \text{ W m}^{-2}$ and $-50 < NEE > 30 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. Periods of low turbulent mixing were identified using a friction velocity (u^*) threshold approach (Papale et al., 2006; Reichstein, Moffat, Maria, Wutzler, & Sickel, 2016), and CO_2 fluxes were excluded when $u^* < 0.14 \text{ m s}^{-1}$. As the site has a limited homogeneous fetch, the spatial representativeness of measured fluxes was assessed using a two dimensional implementation of the Kormann and Meixner (2001) flux footprint model (Neftel, Spirig, & Ammann, 2008). Fluxes were considered representative and retained for analysis when the footprint model indicated > 80 % of the flux originated within the boundaries of the plantation. EC data retention after system downtime and the application of QC are summarised in Table 1. Overall energy balance closure (EBC; Fig. 2) for the EC system at this location (slope of 0.96) was towards the high end of the 0.55 to 0.99 range attained for EC sites, globally (Leuning, Gorsel, Massman, & Isaac, 2012; Stoy et al., 2013; Wilson et al., 2002).

Light response of CO₂ exchange

An empirical modelling approach was used to quantify and compare seasonal and inter-seasonal variations in photosynthetic activity and respiration rates during the months of the growing seasons (April to October). All observations of NEE that passed QC during each calendar month were used to parameterise a modified Michaelis-Menton equation as a function of SW_{in} , using:

$$NEE(SW_{in}) = \frac{-\alpha SW_{in}}{1-(SW_{in}/900)+(\alpha SW_{in}/900)} + R_m, \quad (1)$$

(Carrara et al., 2003; Falge et al., 2001) where: α ($\mu\text{mol CO}_2 \text{ J}^{-1}$) is the ecosystem quantum yield, GPP_{900} ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) is the rate of photosynthesis when SW_{in} is 900 W m^{-2} , and R_m ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) is the mean respiration rate. The model was selected over other forms as it allows the maximum rate of photosynthesis to be compared at a standardised level of SW_{in} .

Gap-filling & flux partitioning

Gap-filling of flux data and the partitioning of NEE into estimates of gross ecosystem production (GEP) and total ecosystem respiration were performed using the REddyProc Package version 0.8-2/r14 (Reichstein et al., 2016) for the R statistical Language (R Core Team, 2017). Data gap-filling of H, LE and NEE was performed using the marginal distribution sampling (MDS) approach (Reichstein et al., 2005). To enable an annual sum to be computed for 2014, missing data at the start of January was gap-filled using EC data collected from 2014-01-09 onwards. Details of the MDS and flux partitioning algorithms have been described in detail and evaluated elsewhere (Desai et al., 2008; Moffat et al., 2007; Papale et al., 2006; Reichstein et al., 2005) and are not repeated here. Gaps in prognostic

micrometeorological variables (SW_{in} , T_{air} and vapour pressure deficit, VPD) required for MDS gap-filling were filled using observations obtained at weather stations located in adjacent fields. T_{air} was used as the driving temperature for flux partitioning as a number of data gaps were present in the T_{soil} record. Uncertainty for individual gap-filled fluxes was estimated as the standard deviation of the observations averaged to fill data gaps (Reichstein et al., 2016). No uncertainties were estimated for GEP and TER as the partitioned CO_2 fluxes represent modelled quantities.

Biomass yield and net ecosystem C balance

In agricultural systems, time-integrated NEE must be combined with data on harvested yields to determine whether a site is a net CO_2 -C source or sink. C exported as harvested biomass (C_{export} , g C m^{-2}) was estimated from farm records. Exported biomass was converted to units of C using a factor of 0.49 (Harris et al., 2017), and assuming a biomass moisture content of 50% at harvest. It was assumed that all exported C would be converted back to atmospheric CO_2 during combustion for bioenergy generation. On the basis of past research at the observation site, it was assumed that emissions/removals of methane (CH_4) and nitrous oxide (N_2O) (Drewer et al., 2012; Finch et al., 2014) were negligible, and that the net ecosystem C balance (NECB, g CO_2 -C m^{-2} year $^{-1}$) could be approximated as:

$$NECB = NEE - C_{export}, \quad (2)$$

where all variables have been defined above.

Results

Environmental conditions

The SRC willow plantation was characterised by seasonal and inter-seasonal variation in environmental conditions during the study period (Fig. 3). Mean annual T_{air} was higher than the 30 year average (of 9.8 ± 0.7 ° C) during all years of the study (Table 2). The majority of months (36 out of 48) experienced mean temperatures that were warmer than long-term climate averages (Fig S1). The spring and early summer months of 2014 and 2017, and the late summer period (August and September) of 2016 were over one standard deviation (SD) warmer than long-term monthly means. December 2015 experienced a mean T_{air} that was more than 5 ° C higher than normal. Annual precipitation sums (Table 2) were within one SD of the 1981 to 2010 mean rainfall average (of 614 ± 93.5 mm year⁻¹). 2015 was notably drier than other years due to lower rainfall during the first half of the year. The annual cycle of volumetric soil water content (VWC) showed broadly similar seasonal patterns across years. Absolute VWC ranged from 26 % (September 2017) to 51 % (June 2014).

Carbon dioxide fluxes

Diurnal and seasonal patterns

Fingerprint plots showing diurnal and seasonal variations in observed and gap-filled NEE are presented in Fig. 4. The general pattern was positive NEE during nocturnal periods and outside the growing season, interspersed by periods of negative NEE during the daytime of the main growth phases. In 2014, daytime NEE started to become more negative from late May onwards as the photosynthetic activity of the vegetation increased as new stems developed and leaf area increased. The highest net uptake rates of 2014 were observed after full canopy closure in July. By contrast, earlier leaf out on the stems of preceding seasons'

growth in later years was associated with more negative CO₂ uptake during spring and earlier seasonal maxima. In 2015, daytime NEE became progressively more positive as defoliation by *P. vulgatissima* progressed from July onwards. The most negative NEE of the study period was observed during June 2016 when mean (\pm standard error of the mean) midday (10:00 to 14:00 UTC) fluxes were $-24.6 \pm 0.7 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. These maximum rates of net CO₂ uptake occurred before any notable leaf damage by willow beetle had been observed in the plantation during that season. The most negative early- and late-season values were measured during the warm conditions of spring and autumn of 2017 and 2016, respectively. The net CO₂ uptake period ended abruptly with the biomass harvest in autumn 2017. Monthly mean nocturnal NEE showed clear seasonal trends, attaining maximum values (mean \pm SD) of 7.3 ± 2 and $7.2 \pm 3 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ during warm conditions of July in 2014 and 2016, respectively.

NEE-light responses

Parameters derived from NEE-light response curves (Eq. 1; see example light response in Fig. 5) for each month of the growing season revealed seasonal and between-year differences in ecosystem photosynthesis and respiration rates (Fig. 6). SW_{in} explained between 50% and 93% of observed variation in monthly NEE (Fig. 6d). Monthly quantum yield (α) values (Fig. 6a) were between $0.025 \pm 0.003 \mu\text{mol CO}_2 \text{ J}^{-1}$ (October 2014) and $0.18 \pm 0.009 \mu\text{mol CO}_2 \text{ J}^{-1}$ (June 2015). Maximum rates of photosynthesis at SW_{in} of 900 W m^{-2} (GEP_{900}) ranged from $4.74 \pm 0.14 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in April 2014, to a maximum of $38.4 \pm 0.6 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in June 2016 (Fig. 6b). Monthly mean respiration rates (R_m) were positively correlated with GEP_{900} ($R_m = 0.15 * GEP_{900} + 1.7 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, $r^2 = 0.79$, $p < 0.05$) and ranged from 2.31 ± 0.1 in April 2014 to $7.58 \pm 0.2 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in July 2014 (Fig. 6c). All three

parameters were lower during the early growing season of 2014 compared to later years, clearly reflecting the early developmental stage of the plantation. In 2015, parameter estimates and net CO₂ uptake rates (see example in Fig. 5) were notably lower than for other years during the main *P. vulgatissima* outbreak between July and September. Other notable inter-annual variations in parameter estimates reflected the influence of warm meteorological conditions on photosynthesis and respiration rates, such as the higher parameter values estimated during warm spring conditions during April 2017, as well as for the warm autumn period during September and October in 2016 (Fig. 6).

Carbon budget

Ecosystem photosynthesis and respiration

The seasonal growth and decay of flux partitioned estimates of GEP and TER and gap-filled NEE are presented as daily sums in Fig. 7. The same data are presented as accumulated monthly totals in Fig S2. The magnitude of peak season GEP (monthly mean \pm SD) ranged from 12.2 ± 2 g CO₂-C m⁻² day⁻¹ in July 2017 to 14.2 ± 3 g CO₂-C m⁻² day⁻¹ during July 2016 (Fig 7b). Total monthly GEP (Fig S2b) ranged from 10.2 g CO₂-C m⁻² month⁻¹ (December 2014) to 439 g CO₂-C m⁻² month⁻¹ (July 2014). Mean (\pm SD) daily TER (Fig 7c) was in the range 0.9 (February 2015) to 8.5 ± 0.6 g CO₂-C m⁻² day⁻¹ (July 2014). Total monthly TER (Fig S2c) was between 26 g CO₂-C m⁻² month⁻¹ (February 2015) and 269 g CO₂-C m⁻² month⁻¹ (July 2014). In spring and early summer of 2014, GEP and TER were both lower than during the corresponding periods of later years, with the magnitude of both fluxes increasing following full canopy closure in July 2014. GEP and TER both showed strong reductions during the *P. vulgatissima* outbreak in 2015. For example, total monthly GEP in August 2015 was only ca. 38% of values estimated for corresponding month of other years. The magnitude

of TER was also lower during the outbreak compared with respective months of other years, but the relative reductions to TER were of a lesser magnitude when compared to relative reductions in GEP.

Net ecosystem exchange

Estimates of daily NEE ranged from -12.5 ± 0.6 g CO₂-C m⁻² day⁻¹ in June 2016 to 5.0 ± 0.2 g CO₂-C m⁻² day⁻¹ (Fig. 7a). The largest net daily losses were observed immediately after harvest in 2017 when TER remained high but GEP was terminated with the removal of the active aboveground biomass. The site switched from a net CO₂ sink to a net source on a number of days when GEP was reduced under low light conditions (Fig. 7a). The number of days with net CO₂ uptake were 122 and 120 in 2014 and 2015, increasing to 196 and 172 for 2016 and 2017, correspondingly. Monthly NEE ranged from a net gain of -195 ± 14 g CO₂-C m⁻² month⁻¹ in June 2016 to a net loss of 65 ± 4 g CO₂-C m⁻² month⁻¹ during October 2014 (Figure S2a).

Cumulative plots (Fig. 8) of daily NEE show net CO₂-C losses were highest during the early part of 2014 and the site did not become a cumulative net sink until the canopy closed in July of that year. Net CO₂-C uptake started earlier during spring of all subsequent years, with the highest early season CO₂-C uptake observed during spring in 2017. Net CO₂-C gains were observed until September during 2014 and until harvest in 2017, and continued into October during the warm autumn period of 2016. By contrast, net CO₂-C accumulation had ended by August in 2015, largely in response to low rates of GEP during the *P. vulgatissima* outbreak. In 2016, lower net CO₂-C uptake during spring (compared to 2017) was compensated by higher net C gains during summer and autumn.

Net ecosystem carbon balance

C balance terms for each year of the observation period are summarised in Table 3. Total accumulated NEE during the complete study period was $-1268 \pm 303 \text{ g CO}_2\text{-C m}^{-2}$. Annual GEP and TER were lowest during 2015 and highest during 2016. TER/GEP ratios showed that around 90% of $\text{CO}_2\text{-C}$ assimilated during photosynthesis was respired during 2014 and 2015, decreasing to 75% during 2016 and 2017. The least negative annual NEE was estimated for the first year of the rotation in 2014. In 2015, annual NEE was of similar magnitude to the previous year, with all of the observed net C uptake in that year occurring before the onset of insect defoliation. The magnitude of annual NEE for 2016, and for the January to November period of 2017 was more than three times more negative than for the two preceding years (Table 3). Dry biomass yield at harvest in September 2017 was 24 Mg ha^{-1} based on farm records, or 6 Mg ha^{-1} when annualised using four growing seasons. C_{export} at harvest was 1183 g C ha^{-1} for the whole production cycle, or $296 \text{ C m}^{-2} \text{ year}^{-1}$ when annualised. On this basis, the NECB indicated the plantation functioned as a small net sink of $-85 \pm 303 \text{ g CO}_2\text{-C m}^{-2}$ over the production cycle, or approximately $-21 \text{ g CO}_2\text{-C m}^{-2} \text{ year}^{-1}$ (e.g. approximately $\text{CO}_2\text{-C}$ neutral) when annualised.

Discussion

For the first time, the C balance of all years of a commercial rotation cycle at a mature SRC willow plantation in the UK has been observed using the eddy covariance (EC) technique. The plantation accumulated $-12.7 \pm 3 \text{ Mg CO}_2\text{-C m}^{-2} \text{ ha}^{-1}$ as NEE during the production cycle, with $11.8 \text{ Mg C ha}^{-1}$ removed as harvested biomass. The annualised dry biomass yield ($6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$) was at the lower end of the range (4 to $15 \text{ Mg ha}^{-1} \text{ year}^{-1}$) reported for SRC willow production in the temperate zone (Searle & Malins, 2014), most likely reflecting the combination of damage by willow beetle (Bjorkman et al., 2000) and the age class of the

plantation. The broadly neutral (annualised) NECB reported in this study ($-21 \text{ g CO}_2\text{-C m}^{-2} \text{ year}^{-1}$) supports the longer-term perspectives provided by studies of soil C, which have shown limited (Rowe et al., 2016) or no change (Walter et al., 2015) in soil organic C following land use change to SRC willow systems. The evidence from this research therefore suggests the primary C benefit of bioenergy production at this location is one of displaced CO_2 emissions from fossil energy sources, rather than net removal of CO_2 from the atmosphere, at least for the time period and conditions encountered during this study.

The current paucity of observational studies at SRC willow plantations currently limits direct comparisons with sites of similar age class in different climatic regions, and with different soil types, land use history and management regimes. However, the range of annual NEE reported in this study was less negative than that reported for a younger willow plantation in Sweden (-331 to $818 \text{ g CO}_2\text{-C m}^{-2} \text{ year}^{-1}$) used for bioenergy production and waste water filtration (Grelle et al., 2007). The more negative annual NEE at the Swedish site is likely explained by the combination of fertilisation by nutrients in waste water and irrigation, as well as broad geographical and climatic influences.

The results of this study contrast with the findings of the only other previous EC study of SRC willow in the UK. Harris et al. (2017) reported (annualised) NEE and NECB values of $-620 \pm 18 \text{ g CO}_2\text{-C m}^{-2} \text{ year}^{-1}$ and $-221 \pm 66 \text{ g CO}_2\text{-C m}^{-2} \text{ year}^{-1}$, respectively, based on observations obtained during two years of a four year rotation at a young plantation established on former grassland in southern England. Differences may be expected between the sites due to past land use history (Rowe et al., 2016), as well as more favourable growing conditions at their more southerly site and/or improved varietal productivity at the younger

plantation. Additionally, the willow beetle mediated defoliation in the current study may have also played a role, with peak season daily NEE values in 2016 (before any notable defoliation in that year) being of broadly similar magnitude to peak growth phase values observed by Harris et al. (2017). The approximately neutral NECB at the mature SRC willow plantation in this study compared to younger sites underlines the importance of quantifying all life stages and management practices when assessing and projecting the C and GHG balance of perennial energy crops, and creates a strong case for extended observational studies designed to track C and GHG dynamics throughout the entire economic lifetime of bioenergy production systems.

The observed defoliation by willow beetle in this study provided an unexpected and novel opportunity to explore such a biotic disturbance event, adding to the limited number of EC studies to have captured CO₂ flux dynamics in treed ecosystems during defoliating insect outbreaks (e.g. Clark et al., 2014, 2010; Olsson et al., 2017; Wilkinson et al., 2012). Although it is speculated that measures to control willow beetle and maximise biomass yield (e.g. Bjorkman and Eklund, 2006; Dalin et al., 2009) would likely translate into increased ecosystem C capture, the lack of comparative data from a non-affected production cycle and/or reference site limits a full quantitative analysis at this time. Despite this data gap, it was clear that photosynthesis, ecosystem respiration and net CO₂ gains were lower during the most severe defoliation event in 2015 compared with corresponding months of other years of the production cycle. Whereas lower photosynthesis and net C uptake were obviously related to reductions in green leaf area during defoliation, lower rates of ecosystem respiration are most likely explained by reductions in foliar respiration rates, as observed at other treed ecosystems experiencing disturbance by defoliating insects (Clark et al., 2010). It is possible that changes to the timing and quality of litter and frass inputs to the soil also served to

enhance soil heterotrophic respiration rates (Clark et al., 2010; Grüning, Simon, Rennenberg, & I-M-Arnold, 2017; I-M-Arnold et al., 2016), although any such increase was clearly outweighed by reductions to foliar respiration. Future research should aim to quantify how biotic disturbance events alter ecosystem C fluxes, the partitioning between auto- and heterotrophic components of total ecosystem respiration, and subsequent influences on ecosystem C storage and biomass yield.

This study represents the first EC observations of net ecosystem CO₂ exchange to be conducted at a mature SRC willow plantation in the UK. Whilst the beetle outbreak clearly influenced the C balance of the plantation during this study, the ecosystem still functioned as a net in situ sink for atmospheric CO₂ in all years within the range -147 ± 70 to -502 ± 84 g CO₂-C m⁻² year⁻¹. However, the NECB of -21 g CO₂-C m⁻² year⁻¹ shows that the SRC willow plantation was close to CO₂-C neutral after harvested biomass was accounted for. Whilst this important finding may appear less favourable than a net increase in ecosystem C storage when considered within the context of decarbonisation and climate change mitigation, the results support the assumption that these crops are approximately C neutral as is often adopted in bioenergy life cycle assessments (Rowe et al., 2011). This finding also supports claims that bioenergy with C capture and storage (BECCS) may prove viable in delivering negative GHG emissions required to meet domestic and international emissions reduction targets as and when such technology becomes viable (Energy Technologies Institute, 2015; Rosen, 2018). Understanding and modelling the C cycle implications of bioenergy cultivation over larger geographical areas clearly requires additional observational data from a broader range of locations and over longer time frames. Further work is also needed to address the impacts of insect defoliation on yield and the cycling of C and other nutrients. Despite these knowledge gaps, this study represents an important step forward in understanding the C

balance of SRC willow production and provides a valuable data resource for future work on this topic.

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All data used in this study (Morrison et al., 2019) are available for download via the Environmental Information Data Centre (EIDC).

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Tables

Table 1. Eddy covariance data capture between 2014 and 2017. Values represent the percentage of all potentially available eddy covariance observations that were retained for analysis after system outages and data rejection during quality control (see main text for details).

Year	H (%)			LE (%)			NEE (%)		
	Day	Night	All	Day	Night	All	Day	Night	All
2014	78	68	72	71	48	58	66	50	57
2015	88	73	79	72	52	61	65	52	58
2016	88	71	79	76	49	61	70	50	59
2017	81	71	75	71	49	59	66	50	58
All years	84	70	76	72	49	60	67	51	58

Table 2. Summary of annual meteorological data for Lincolnshire, UK for 2014 to 2017.

Annual values are from the long-term meteorological observation station at Waddington, Lincolnshire, UK. Data supplied by the Met Office.

Year	Air temperature (° C)	Precipitation (mm year⁻¹)
2014	11.0 ± 4.6	624
2015	10.5 ± 4.3	531
2016	10.3 ± 5.1	653
2017	10.7 ± 4.9	584

Table 3. Estimates of time integrated carbon dioxide fluxes obtained between 2014 and 2017 at a mature short rotation willow plantation. NEE is net ecosystem carbon dioxide exchange ($\text{g CO}_2\text{-C m}^{-2}$); GEP is gross ecosystem production ($\text{g CO}_2\text{-C m}^{-2} \text{ year}^{-1}$); TER is total ecosystem respiration ($\text{g CO}_2\text{-C m}^{-2} \text{ year}^{-1}$). The values shown for 2017 represent the period 2017-01-01 to 2017-11-26.

Year	NEE	GEP	TER	TER/GEP
	$\text{g CO}_2\text{-C m}^{-2}$	$\text{g CO}_2\text{-C m}^{-2}$	$\text{g CO}_2\text{-C m}^{-2}$	--
2014	-147 ± 70	1431	1284	0.90
2015	-156 ± 73	1383	1228	0.89
2016	-502 ± 84	1935	1433	0.74
2017	-462 ± 75	1900	1438	0.76
Total	-1268 ± 303	6649	5383	0.81

Figure captions

Figure 1. Photographs showing progressive leaf defoliation caused by defoliation by willow leaf beetle (*Phratora vulgatissima*) herbivory during the 2015 growing season. Dates are provided on each image (photographs: R. Morrison, 2015).

Figure 2. Energy balance closure at a short rotation willow coppice plantation in Lincolnshire, UK. The regression equation, determination coefficient (r^2) and number of data points (n) are shown on the graph. Data are all thirty minute flux observations that have passed quality control for thirty minute periods when all energy balance terms were available. The solid black line shows the linear regression. The dashed line shows the 1:1 linear relationship.

Figure 3. Daily meteorological and soil physics observations obtained at a short rotation willow coppice plantation in Lincolnshire, UK. Panels show: (a) total incoming shortwave radiation; (b) Mean daily air temperature (line) with maximum and minimum daily air temperatures (polygon); and (c) total daily precipitation and the mean volumetric soil water content of the upper 0.3 m of the soil profile.

Figure 4. Fingerprint plots showing diurnal and seasonal variation in net ecosystem carbon dioxide exchange (NEE) measured at a mature commercial SRC willow plantation using eddy covariance between 2014 and 2017. The top panels show NEE observations retained after system outages and the application of quality control. The percentage of eddy covariance data capture is provided in Table 1. The lower panels show a combination of

observed and gap-filled NEE. Positive flux densities denote losses from surface to atmosphere and negative values the reverse.

Figure 5. Example light response curves for the months of June (white points) and August (grey points) in 2015 (top panel) and 2017 (lower panel). The SRC willow plantation experienced severe defoliation during an outbreak of willow leaf beetle during the 2015 growing season. Parameters of the fitted curves are presented in Fig. 6. Positive flux densities denote losses from surface to atmosphere and negative values the reverse.

Figure 6. Monthly light use and respiration parameters estimated from a model describing the response of net ecosystem carbon dioxide exchange to changes in incoming short wave radiation. Panels show: (a) the quantum yield of photosynthesis (α); (b) the rate of photosynthesis when incoming short wave radiation is 900 W m^{-2} (GEP_{900}); (c) monthly average total ecosystem respiration (R_m); and (d) determination coefficients (r^2) for each monthly fit.

Figure 7. Daily sums of (a) net ecosystem carbon dioxide exchange (NEE); (b) gross ecosystem production (GEP); and (c) total ecosystem respiration (TER). All values are in $\text{CO}_2\text{-C m}^{-2} \text{ day}^{-1}$. Positive NEE flux densities denote fluxes from surface to atmosphere and negative values denote the reverse.

Figure 8. Cumulative net ecosystem carbon dioxide exchange for 2014 to 2017. Note that observations were only made until November in 2017. Shaded areas show accumulated daily uncertainty estimates. Daily uncertainties were derived as the sum of squares of the standard deviations estimated for observed and gap-filled estimates of net ecosystem CO_2 exchange.















